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Structural Resilience in the Cobalt Industry Chain Trade Network: Evolution and Evaluation

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Abstract

As a strategic mineral, cobalt is a new focus of global competition. Studying its industry chain via trade network structural resilience is crucial for optimizing industrial layout and enhancing security. This study constructs a degree distribution and degree correlation bivariate model to analyze the resilience evolution of global upstream, midstream, and downstream cobalt trade networks from 2011 to 2023. Conclusions show: (1)Regarding node characteristics, China, the US, and Germany are active core nodes. China plays a multidimensional role: heavily relying on upstream raw ore imports, acting as a midstream processing hub, and holding prominent downstream export advantages; (2)Regarding hierarchical structure, overall network differentiation is minor. The upstream hierarchy is weakening with intensified flattening, while midstream and downstream hierarchies are slightly strengthening with prominent stereoscopic features; (3)Regarding network matching properties, the overall network exhibits disassortative features. Upstream disassortative features are slightly enhancing via close cross-tier interactions, whereas midstream and downstream assortative features are increasing, weakening cross-tier connectivity and undermining matching resilience; (4)Regarding resilience evolutionary levels, structural resilience fluctuates significantly, ranking as downstream greater than upstream, and upstream greater than midstream. The downstream shows robust adaptive repair, while the midstream, constrained by capacity agglomeration barriers, exhibits sluggish recovery and the sharpest decline in risk resistance. Policy recommendations include: perfecting safeguard systems for a sound industrial ecology; deepening overseas deployment to fortify supply; advancing collaborative restructuring for independent controllability; and expanding multilateral trade networks for new competitive advantages. This study provides a valuable reference for safeguarding China's strategic mineral security and stable industry operations.

Keywords

Cobalt; Industry Chain; Trade Network Structural Resilience

1. Introduction

As a vital strategic mineral, cobalt is widely used in high-tech fields like new energy

and aerospace, making it a new focus of global power competition. Currently, uncertainties such as geopolitical conflicts and extreme weather severely disrupt global resource supplies. In this complex environment, integrating resilience into risk management has become a consensus. International trade forms a complex network, and an optimized structure is key to mitigating risk propagation. Therefore, exploring the resilience evolution of the global cobalt trade network provides a crucial basis for enhancing industry chain security. The resilience concept has evolved from engineering resilience to evolutionary resilience, emphasizing proactive adaptation to external changes. Recently, integrating resilience research with complex network theory shows that robust networks can swiftly absorb shocks. In quantifying network resilience, Xie et al. utilized hierarchy and matching properties to analyze urban networks. Currently, hierarchy and matching properties are widely recognized as representative evaluation indicators for network structural resilience.Currently, research on strategic mineral security from a systemic resilience perspective remains limited. Traditional cobalt trade literature mainly focuses on specific countries, analyzing sources, production, consumption, and supply relationships to evaluate security via indicator systems. For instance, Zhao et al. revealed a core-periphery evolution where global cobalt trade concentrates in a few nations. Li et al. quantified multi-dimensional risks from import concentration and trade intermediation across the cobalt life cycle. Guo et al. used a multi-attribute gravity centrality algorithm to dynamically map risk propagation and vulnerable links along the industry chain. Although existing studies have explored spatial patterns and risk propagation, research focusing on the dynamic resilience evolution of the cobalt trade network remains insufficient, falling short of current industrial needs and the realities of great power competition.Therefore, focusing on the cobalt industry chain and utilizing global upstream, midstream, and downstream trade data from 2011 to 2023, this study constructs a "degree distribution-degree correlation" bivariate model. It evaluates the structural resilience levels and evolutionary trends of trade networks across all segments, providing a valuable reference for safeguarding the security and stability of China's cobalt industry chain.

2. Data and Methodology

2.1. Data Sources

Currently, the selection of products for the cobalt industry chain remains unstandardized. Drawing on the methodology of Zhao et al. (2022), this paper targets commodities containing the keyword "cobalt" recorded in the United Nations Comtrade Database from 2011 to 2023. Trade data for cobalt ores and concentrates (HS2605) and cobaltates (HS284190) were extracted respectively. The corresponding end-use application for these two products is lithium batteries (HS850650), and these three traded products form a complete corresponding

relationship along the industry chain. Table 1 lists the relevant products and their codes within the cobalt industry chain. Constrained by statistical data sources, detailed data for downstream sub-segment products such as catalysts and cemented carbides are unavailable. Therefore, these three traded products are selected as the representative products for the upstream, midstream, and downstream segments of the industry chain, respectively. Bilateral trade data between countries include information such as reporting country, partner country, trade value, commodity weight, and trade flows. Generally, countries worldwide exercise stricter supervision over import trade; therefore, this paper primarily adopts the import perspective to obtain commodity trade data.

Table 1. Related Products and Codes of the Cobalt Industry Chain

Industry Chain	HS Code	Product Name	Covered Years
Upstream	HS2605	Cobalt Ores and Concentrates	2011-2023
Midstream	HS284190	Lithium Cobalt Oxide and other Cobalt Compounds	2011-2023
Downstream	HS850650	Lithium Batteries	2011-2023

2.2. Selection of Network Structural Resilience Indicators

This study constructs a degree distribution-degree correlation bivariate evaluation model for trade network structural resilience evolution to comparatively analyze the types and evolutionary trends of structural resilience across the upstream, midstream, and downstream cobalt trade networks.

Network hierarchy: Network hierarchy refers to the hierarchical distribution of external connection strengths among node countries within the trade network. A higher hierarchy indicates a broader span of node levels from low to high. The hierarchy of the cobalt industry chain trade network can be measured using the degree and degree distribution of the node countries. Drawing on the rank-size rule, all nodes in the network are sorted based on their degree values to establish a power-law relationship. In the specific calculation of the degree distribution slope, a logarithmic transformation is applied to both the degree value of each node in the network and its corresponding rank order. Subsequently, linear regression fitting is performed on these two sets of log-transformed data, and the slope of the resulting regression line is exactly the value of a.

Network matching properties: Network matching properties refer to the correlation between the degrees of node countries in a network. Based on the connections between nodes and their similar peers, networks can be classified into assortative networks and disassortative networks. Specifically, assortative networks include core-core and periphery-periphery connection structures; conversely, disassortative networks feature a core-periphery connection structure. The matching properties of the cobalt industry chain trade network can be measured using degree correlation. In the specific calculation of the correlation coefficient b, the average

degree of all adjacent nodes for each node in the network is first calculated. Subsequently, linear regression fitting is performed between each node's own degree and its corresponding average degree of adjacent nodes, and the slope of the resulting regression line is exactly the value of b. If b is greater than zero, it indicates that nodes with high degrees tend to connect with similarly high-level nodes, making it an assortative network; conversely, if b is less than zero, the network is a disassortative network.

To quantify the evolutionary level of network structural resilience, based on the research of Xie et al., this study constructs a "degree distribution-degree correlation" bivariate evaluation model for trade network structural resilience evolution and determines a comprehensive index to quantify the magnitude and quality of resilience evolution. As shown in the figure below, P and Q are the perpendicular distances from point A or point B to the reference line where the change in the degree correlation coefficient equals the absolute value of the change in the degree distribution slope, and L is the distance from that point to the origin. When the point falls in the blue recession area (denoted by -), it indicates that the network structural resilience is weakened; conversely, when the point falls in the yellow enhancement area (denoted by +), it indicates that the resilience is improved. The greater the distance L to the origin, the larger the magnitude of resilience evolution. P/Q represents the quality of resilience development, with a larger value indicating better quality or a more pronounced recession. The evolutionary level of network structural resilience, R, is the product of P/Q and L.

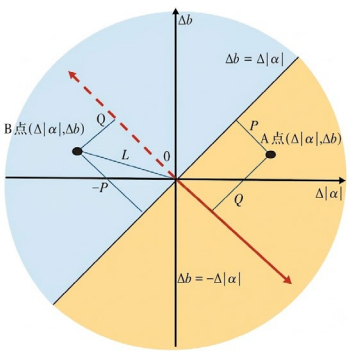


Figure 1. Evaluation Model for the Evolutionary Level of Network Resilience

3. Analysis of Node Degree

Node degree refers to the number of nodes directly connected to a specific node. It is divided into indegree and outdegree to measure the relative position of a node in the network. Nodes with higher degree centrality have more connections, resulting in greater network influence and importance.

In the upstream product trade, imports are concentrated in Germany, France, the Netherlands, China, and South Africa, while exports are concentrated in the United Kingdom, Germany, the United States, China, and the Democratic Republic of the Congo. China was a core importing country during the early and middle stages of the observation period, but its leading position has recently declined. This is because Chinese enterprises have accelerated direct investment and capacity transfer in resource countries like the Democratic Republic of the Congo, reducing their reliance on direct raw ore imports.

For midstream products, the main importing countries are China, South Korea, the Netherlands, and Germany, while the main exporting countries are the United States, Germany, and China. Driven by the industrialization of power batteries, China and South Korea have massive import demands for intermediate goods with high added value. Meanwhile, the United States and Germany rely on technological advantages to secure export shares for premium products.

In the downstream product trade, Western countries such as France, Germany, the Netherlands, and the United States serve as the main importing countries due to their automotive electrification transition and domestic capacity gaps. The main exporting countries are China and the United States. During the latter half of the observation period, China leveraged its new energy vehicle industrial policies and manufacturing advantages at scale to surpass the United States. This established a dominant export position for terminal products and caused a significant alternation in the network status of the core nodes between China and the United States.

4. Analysis of Trade Network Resilience in the Cobalt Industry Chain

4.1. Trade Network Hierarchy

In the trade network, the degree distribution index a usually appears as a negative value. The absolute value of its fitted curve slope characterizes the hierarchical and flattening features within the network. Through calculation, the absolute values of the degree distribution index across various segments of the cobalt industry chain show little difference and minor evolution during the observation period of this study. The network hierarchy is manifested as follows: it is highest in the midstream, followed by the downstream, and lowest in the upstream. This indicates that the overall network hierarchical differentiation is small, and the status of the core node clusters is relatively fixed.

From the perspective of dynamic evolution, the variation magnitude of the absolute values of the degree distribution index across all segments is generally small, and the evolution of the network hierarchical structure is relatively gradual. The curve slope of the upstream network decreased from 1.09 in 2011 to 1.01 in 2023, indicating that its internal hierarchy weakened and its flattening characteristics strengthened. The hierarchy of the midstream and downstream shows a slightly

upward trend. The midstream slope rose slightly from 1.363 in 2011 to 1.367 in 2023, and the downstream slope rose from 1.241 to 1.285. This indicates that the internal hierarchy in the midstream and downstream has slightly strengthened, while the flattening characteristics have relatively weakened.

4.2. Trade Network Matching Properties

The matching properties of the trade network can reflect the selective linking preferences among nodes with different connection scales in the network. This study further calculates the degree correlation index b of the cobalt industry chain trade network from 2011 to 2023. During the sample period, the degree correlation index b of each segment is less than zero, indicating that the overall cobalt industry chain trade network exhibits disassortative characteristics. That is, core nodes with larger degree values are more inclined to establish trade connections with peripheral nodes with smaller degree values.In terms of dynamic evolution, the upstream degree correlation index slightly decreased from -0.163 in 2011 to -0.168 in 2023, showing slightly strengthened disassortative characteristics. This indicates that interactions across different levels between core and peripheral nodes remain close, which enhances the breadth of resource allocation and the matching resilience of the upstream network. Conversely, the degree correlation indices for the midstream and downstream show a significant upward trend. The midstream index rose from -0.563 to -0.341, and the downstream index increased from -0.426 to -0.395. This reflects strengthened assortativity in the midstream and downstream, meaning nodes prefer connections within the same tier (namely, core interconnecting with core, and peripheral interconnecting with peripheral). Such a preference for connections within the same layer reduces internal interactions across different tiers, leading to network hierarchy differentiation, thereby weakening the matching resilience of the midstream and downstream networks to a certain extent.

Table 2. Measurement Results of Degree Distribution and Degree Correlation in the Trade Network of the Cobalt Industry Chain

Year	Industry Chain	|a|	b
2011	Upstream	1.090	-0.163
	Midstream	1.363	-0.536
	Downstream	1.241	-0.426
2023	Upstream	1.010	-0.168
	Midstream	1.367	-0.341
	Downstream	1.285	-0.395

4.3. Analysis of the Evolutionary Level of Trade Network Resilience

To intuitively quantify and measure the evolutionary level of trade network resilience in the cobalt industry chain, this study constructs a bivariate two dimensional matrix evaluation model. The calculation results show that the

comprehensive index R values for the overall resilience evolution of the upstream, midstream, and downstream are -0.0707, -0.2142, and +0.0093, respectively.

From the perspective of evolution direction, both the upstream and midstream of the cobalt industry chain show a direction of resilience recession, while the downstream network presents a weak upward trend in resilience. Among them, the evolutionary level of network resilience in the midstream is the lowest, and its resilience recession is the most obvious. Meanwhile, the L value, which represents the magnitude of resilience change, shows a characteristic where the midstream at 0.2220 is greater than the upstream at 0.0802, which in turn is greater than the downstream at 0.0538. This indicates that the resilience of the midstream processing network fluctuates most violently under external influences, whereas the overall magnitude of resilience change in the upstream and downstream networks is relatively gradual.To further deconstruct the dynamic evolution path of network resilience from 2011 to 2023, this study splits the measurement results of network degree distribution and degree correlation across different periods into four stages: 2011 to 2014, 2014 to 2017, 2017 to 2020, and 2020 to 2023. A1 to A4, B1 to B4, and C1 to C4 represent the four evolutionary stages of network structural resilience for the upstream, midstream, and downstream of the cobalt industry chain, respectively. From the split data, it can be seen that the trade network resilience of all segments in the cobalt industry chain remained in a state of significant fluctuation during the sample period.

Specifically, the upstream network resilience continuously improved during stages A1 to A2. However, in stage A3, namely from 2017 to 2020, affected by external shocks such as global trade games and the pandemic, the resilience decayed substantially, with the R value dropping to -1.6086. Subsequently, in stage A4 from 2020 to 2023, it quickly adjusted and strongly recovered, with the R value rebounding to 1.3930. Although an ideal autonomous repair capability emerged in the final period, it failed to fully offset the previous decline, leading to a slight recession in the overall ability to adapt to risks.The evolution of midstream network resilience is mainly dominated by negative drivers. A substantial recession appeared early in stage B1 with an R value of -0.7037. Even though a certain degree of recovery was achieved in stage B2 with the R value reaching 0.2276, it fell into continuous recession again during stages B3 and B4 under the volatile international situation. This repetitive trajectory that leans toward vulnerability makes it the segment with the most severe decline in the ability to resist risks across the entire industry chain.In contrast, the downstream network resilience demonstrates a strong adaptive repair capability. After a slight increase in stage C1, the downstream R value also experienced continuous recession in stages C2 and C3 due to external shocks, becoming particularly evident in stage C3 where the R value dropped to -0.5670. However, in stage C4, driven by the explosion of end markets such as global new energy vehicles and supply chain restructuring, the downstream resilience

achieved an extremely high positive rebound, with the R value reaching 1.3324. This reversed the previous recession trend and overall achieved a healthy resilience evolution.

Overall, over the past decade or so, the structural resilience of the cobalt industry chain trade network has fluctuated significantly. The comprehensive evolutionary level presents a pattern where the downstream is the best, followed by the upstream, and the midstream is the weakest. It is worth noting that all segments experienced weak recovery when facing major external shocks from 2017 to 2020. However, after 2020, the upstream and downstream demonstrated excellent adaptive and restructuring capabilities, while the midstream resilience repair was relatively delayed due to the high agglomeration barriers of processing hubs.

Table 3. Comprehensive Index of the Evolutionary Level of Structural Resilience in the Cobalt Industry Chain Trade Network

Industry Chain	Evolutionary Trend	P	Q	P/Q	L	R
Upstream(A)	-	0.053	0.060	0.882	0.080	-0.071
Midstream(B)	-	0.154	0.160	0.965	0.222	-0.214
Downstream(C)	+	0.009	0.053	0.173	0.054	+0.009

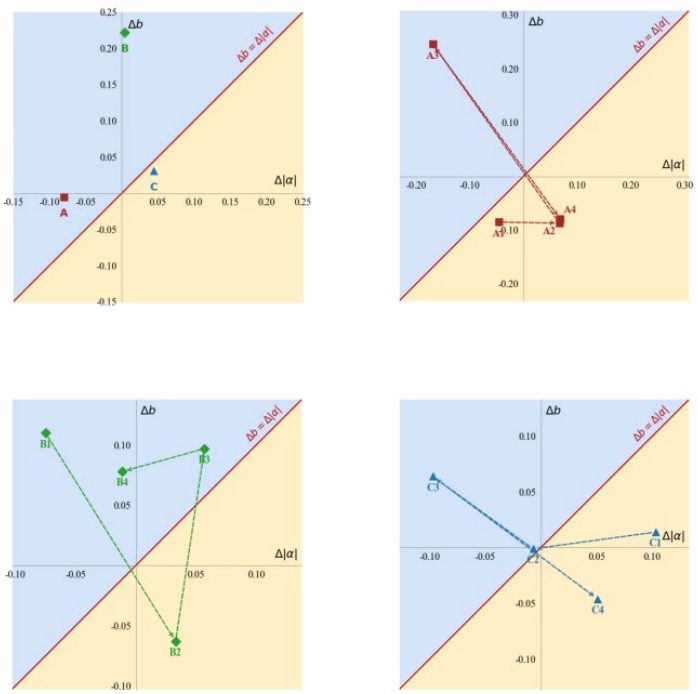


Figure 2. Coordinate System of the Evolutionary Level of Resilience in the Cobalt Industry Chain Trade Network

5. Conclusions and Policy Implications

5.1. Research Conclusions

Based on the bivariate model of degree distribution and degree correlation, this

study analyzes the structural resilience evolution of the global cobalt industry chain trade networks from 2011 to 2023. The main conclusions are as follows.

(1) In terms of node characteristics, China, the United States, Germany, and the Netherlands are core nodes. China is a midstream processing hub heavily reliant on upstream imports, holding a downstream export advantage. The United States and Germany have stable upstream and midstream exports, Western countries dominate the dense downstream network, and the regional transit role of the Netherlands is increasingly strengthening.

(2) Regarding the network hierarchy structure, differences across segments are small, and the status of core clusters is relatively fixed. In terms of evolution trends, the upstream hierarchy weakened while its flattening features strengthened. Conversely, the midstream and downstream hierarchies slightly strengthened while their flattening features relatively weakened.

(3) With respect to network matching properties, all segments exhibit overall disassortativity. The upstream disassortativity strengthened, and close interactions across different layers improved its matching resilience. The midstream and downstream assortativity strengthened, and the preference for connections within the same tier weakened their matching resilience.

(4) As for the evolutionary level of resilience, the overall pattern shows that the downstream is the strongest, followed by the upstream, with the midstream being the weakest. The downstream has the best adaptive repair capability and achieved positive evolution. The upstream showed obvious rebound and recovery after external shocks. The midstream, restricted by capacity agglomeration barriers, experienced the most obvious recession.

5.2. Policy Recommendations

Based on the preceding analysis of the trade network evolution and structural resilience of the global cobalt industry chain, this study proposes the following policy recommendations to cope with the complex and volatile international environment and to ensure the security of strategic mineral resources and the smooth operation of the industry chain in China.

(1) Sound the industry guarantee system and build a good ecology. Improve the strategic stockpiling and dynamic release mechanisms for cobalt resources to stabilize market fluctuations. Vigorously develop recycling technologies for used batteries and establish a traceability system. Meanwhile, construct a trade risk warning framework and emergency plans to enhance the overall damage resistance capability of the industry chain.

(2) Deepen the overseas resource layout and secure the supply bottom line. Guide enterprises to conduct diversified mineral investments and capacity cooperation in core production areas such as Africa. Simultaneously, overcome core technologies like raw ore purification to consolidate the advantage of China as a global processing

and conversion hub.

(3) Promote the collaborative restructuring of the industry chain and strengthen independent controllability. Cultivate leading enterprises with global resource allocation capabilities to enhance control over key links such as midstream processing. Relying on massive domestic demand and manufacturing advantages, lead the optimization of regional industry chains to break the lock in barriers of low added value, thereby comprehensively improving overall network resilience.

(4) Expand the multilateral trade network and build new competitive advantages. Relying on initiatives like the Belt and Road, precisely meet the demands of emerging markets in Southeast Asia, Latin America, and the Middle East. By deepening international cooperation, dilute the reliance on a single market and create a secure globalized cobalt industry chain with high added value.

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